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A New Swarm Intelligence Approach for Optimal Chiller Loading for Energy Conservation

Mohd Herwan Sulaiman[a*], Hassan Ibrahim[b], Hamdan Daniyal[c], Mohd Rusllim Mohamed[d]

[a,c,d]*Faculty of Electrical & Electronics Engineering, Universiti Malaysia Pahang, 26600 Pekan Pahang, Malaysia*
[b]*Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan Pahang, Malaysia*

Abstract

This paper employs a recent swarm intelligence technique to solve optimal chiller loading (OCL) problem, namely differential search (DS) algorithm. In general, significant energy savings can be obtained by optimizing chiller operation and design in heating, ventilation and air-conditioning (HVAC) systems. In this paper, partial load ratio (PLR) of the chiller is used as parameters to be optimized where the power consumption in kW is used as objective function to be minimized. In order to show the effectiveness of the proposed technique, the comparison with other techniques has been done and analyzed.

Keywords: Differential Search Algorithm; Heating; Ventilation and Air-Conditioning (HVAC) System; Optimal Chiller Loading (OCL); Partial Load Ratio (PLR); Swarm Intelligence

1. Introduction

Optimal chiller loading (OCL) problem emerge due to awareness for energy conservation especially for multiple chiller system which requires huge power consumption. Multiple chiller system is typically utilized in air conditioning system since it has ability to operate flexibly, less disruption maintenance and can be operated as standby capacity. On the other hand, to operate the system optimally so that the energy

* Corresponding author. +609 4246140
E-mail address:herwan@ump.edu.my

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can be reduced becoming the major issue since there are various performances of individual chiller in term of characteristics and capacities.

To date, there are several techniques that have been proposed to solve OCL problem especially by adopting recent swarm intelligence approach. Particle swarm optimization (PSO) has been applied in solving OCL problem in (Ardakani, Ardakani, & Hosseinian, 2008), where the comparison among PSO, binary genetic algorithm (BGA) and continuous genetic algorithm (CGA) was made. The same PSO approach also has been proposed in (Lee & Lin, 2009), where different test systems were utilized and the performance of PSO was compared with Lagrange method (LGM) and GA. Nevertheless, the results obtained still can be improved.

The implementation of differential evolution (DE) technique into OCL problem has been presented in (Lee, Chen, & Kao, 2011). DE is known as a simple algorithm which is extended from GA but it more relies on mutation operator compared to crossover operator. However, there are many variants of DE that can be used which sometimes it hard to choose the best variant to solve a problem. The recent swarm intelligence technique, namely improved firefly algorithm (IFA) to solve OCL has been proposed in (Coelho & Mariani, 2013). The comparison with original FA together with other techniques was discussed. Despite good results were obtained; the proposed IFA violated an inequality constraint suggested by the manufacturer which will be highlighted later.

This paper proposes a new swarm intelligence technique, viz. differential search (DS) algorithm for solving OCL problem. Partial load ratio (PLR) of the chiller is used as the variables to be optimized and the energy consumption in kW is utilized as objective function to be minimized. The rest of the paper is organized as follows. The system structure of multiple chillers is discussed briefly in Section 2. Brief description of DS algorithm and the implementation of DS to OCL problem are discussed in Section 3 and 4, respectively. Section 5 presents simulation result and discussion and finally conclusion is stated in Section 6.

2. Multiple Chiller System

A multiple chiller system constitutes of multiple chillers connected by parallel or series piping to a distribution system. Each chiller can be operated at different capacities to meet different cooling demands and this allows the chiller system to operate at its most efficient point (Lee, et al., 2011).

In this system, by considering a system with all-electric cooling, the optimum operation is achieved when the energy consumption of the system is minimized and the cooling load is satisfied. PLR of a chiller is defined as (Ardakani, et al., 2008):

$$PLR = (\textit{chiller load}/\textit{design capacity}) \tag{1}$$

The energy consumption of centrifugal chiller is a convex function of its PLR at a given wet-bulb temperature (Coelho & Mariani, 2013) is given below:

$$P_i = \alpha_i + \beta_i PLR_i + \sigma_i PLR_i^2 + \delta_i PLR_i^3 \tag{2}$$

where α_i, β_i, σ_i and δ_i are coefficients of power curve of the ith chiller.

The objective function in OCL problem is to find the minimum sum of energy consumption of the chillers, (J) as stated in the following expression:

$$J = \min \sum_{i-1}^{n} P_i \tag{3}$$

where n is the total number of chillers and Eqn. (3) is subject to equality and inequality constraints expressed in Eqns. (4) and (5), respectively, as follow:

$$\sum_{i=1}^{n} PLR_i * Q_i = CL \tag{4}$$

$$PLR_i \geq 0.3 \tag{5}$$

where Q_i is capacity of the ith chiller and CL is a system cooling load. Eqn. (5) is the constraint suggested by the manufacturer which is that partial load of each operating chiller cannot be less than 30%.

3. Differential Search Algorithm

DS algorithm is a recent swarm intelligence technique inspired by migration of living beings during climate change of the year. The behavior of migration for superorganisms is starting by changing their position from one habitat to more fruitful habitat. The movement of superorganisms is utilizing the concept of Brownian like motion (Civicioglu, 2012).

It is assume that random movement of population is corresponding to the artificial-superorganism migration to global optimum solution of the problem. During the migration, the artificial-superorganism tests a suitable position to stop over for a temporary before continue to find the fruitful areas. DS strategy may use more than one individual simultaneously in searching the best solution for the problem in hands. In addition, DS only requires two control parameters, i.e. *p1* and *p2* and the algorithm is very simple. Nevertheless, it requires large iteration to obtain good solution. Pseudo code for DS can be obtained in (Civicioglu, 2012).

4. DS for OCL Problem

Initially, member of artificial-organisms are generated randomly to create a population. The population consists of candidate for solution which is for this case is the value of PLR and expressed as follows:

$$X = \begin{bmatrix} x_1^1 & \cdots & x_{nc}^1 \\ \vdots & \ddots & \vdots \\ x_1^{pop} & \cdots & x_{nc}^{pop} \end{bmatrix} \tag{6}$$

where pop is the number of population and nc is the number of chiller plant in the system. The mechanism of finding *stopover* site at the areas is using a random searching process. Multiple random processes are utilized in DS until the optimal results are obtained by the migration of artificial-organisms. Eqn. (3) was used in the evaluation process of OCL problem.

In order to handle with the inequality constraint i.e. Eqn. (5), when the searching solution resulted less than 30%, the algorithm is design to choose the boundary value, for this study is 0.3. While for equality constraint, i.e. Eqn. (4), the utilization of penalty function is employed. The penalty function is reflected to the summation mismatch and embedded in the Eqn. (3) as follow:

$$J = (J) + PF * abs[\sum_{i-1}^{n} (PLR_i * Q_i) - CL] \tag{7}$$

where PF is the penalty factor. The program is run until the maximum iteration is reached and the algorithm will be stop.

5. Simulation and Discussion

For this study, 6-chillers system is used to show the effectiveness of proposed DS algorithm. The simulation for solving OCL problem was implemented on MATLAB. The parameter for this system is tabulated in Table 1.

Table 1. Chillers data for 6-unit system

Chiller	a_i	b_i	c_i	Capacity (RT)
1	399.345	-122.12	770.46	1280
2	287.116	80.04	700.48	1280
3	-120.505	1525.99	-502.14	1280
4	-19.121	898.76	-98.15	1280
5	-95.029	1202.39	-352.16	1250
6	191.750	224.86	524.04	1250

Performance of DS algorithm for solving OCL problem for 6-unit system is shown in Table 2. From this table, it can be seen that the comparison has been made between DS and IFA (Coelho & Mariani, 2013) for various load *CL*. The best, average and worst results are depicted in this table for both techniques where for DS, 20 simulation runs have been conducted. It can be noted that the biggest standard deviation for DS is emerged at 75% of RT, which is 2.8338. The main issue that needs to be highlighted in this simulation is that the results obtained by IFA for 75% and 70% of RT are seems to be good but the truth is the results are violating Eqn. (5) which brings the power consumption lower for this system.

Table 2. Performance of DS and IFA for 6-unit system

Techniques	Load *CL* (kW)	Best (kW)	Average (kW)	Worst (kW)	Standard deviation
DS	6858 (90%)	4738.5752	4738.5757	4738.5766	0.0004
IFA	6858 (90%)	4738.575	4738.575	4738.576	0.0002
DS	6477 (85%)	4421.6486	4421.6489	4422.6499	0.0003
IFA	6477 (85%)	4421.649	4421.649	4422.650	0.000231
DS	6096 (80%)	4143.7064	4143.7092	4144.7265	0.0051
IFA	6096 (80%)	4143.706	4165.210	4208.276	30.929
DS	5717 (75%)	3904.7485	3905.3916	3917.431	2.8338
IFA	**5717 (75%)**	**3840.063**	**3868.776**	**3905.903**	**33.027**
DS	5334 (70%)	3625.7703	3625.7717	3625.7884	0.0042
IFA	**5334 (70%)**	**3507.286**	**3541.167**	**3685.821**	**68.891**

In order to show the effectiveness of the proposed DS, comparisons with other algorithms also had been done. This is summarized in Table 3, where the best results of the details of chillers output are shown for DS together with PSO (Ardakani, et al., 2008) and IFA. The results in this table clearly show that DS gave the best results among others in term of quality solution. The boldface shows the errors in IFA where the results are in negative value for 75% and 70% of RT due to constraint violation which had been mentioned previously.

Table 3. Optimal chiller loading using DS, IFA and PSO

Load (RT)	Proposed DS				IFA			PSO		
	Chiller	PLR	kW	Total (kW)	PLR	kW	Total (kW)	PLR	kW	Total (kW)
6858 (90%)	1	0.8127	809.0115	4738.575	0.8128	809.0561	4738.576	0.8026	797.6788	4739.785
	2	0.7496	740.7352		0.7495	740.6313		0.7799	775.6981	
	3	1	903.345		1	903.345		0.9996	903.1638	
	4	1	781.489		1	781.489		0.9998	781.3991	
	5	1	755.201		1	755.201		0.9999	755.1979	
	6	0.8386	748.7935		0.8386	748.852		0.8183	726.6468	
6477 (85%)	1	0.7276	718.4155	4421.649	0.7278	718.5762	4421.649	0.7606	752.2134	4423.053
	2	0.6563	641.3152		0.6562	641.2379		0.6555	640.5199	
	3	1	903.345		1	903.345		1	903.3449	
	4	1	781.4889		1	781.489		1	781.4889	
	5	1	755.201		1	755.201		1	755.201	
	6	0.7165	621.883		0.7164	621.8		0.6835	590.2852	
6096 (80%)	1	0.6427	639.1437	4143.706	0.6427	639.1289	4143.706	0.6591	653.5696	4147.806
	2	0.5626	553.877		0.5626	553.898		0.5798	569.0161	
	3	1	903.345		1	903.345		0.9991	902.8647	
	4	1	781.489		1	781.489		0.9979	780.0799	
	5	1	755.201		1	755.201		0.9921	751.2365	
	6	0.5945	510.6507		0.5945	510.6442		0.571	491.0385	
5717 (75%)	1	0.5577	570.8792	3904.749	0.84222	843.0046	3840.063	0.7713	763.4782	3920.964
	2	0.4692	478.8736		0.78137	777.3214		0.7177	705.3382	
	3	1	903.345		**2E-06**	**-120.502**		0.3	292.0994	
	4	1	781.489		1	781.4855		0.9991	780.8389	
	5	1	755.201		1	755.201		1	755.201	
	6	0.4725	414.9607		0.88705	803.5604		0.7187	624.0084	

Table 3. Optimal chiller loading using DS, IFA and PSO (continued)

Load (RT)	Proposed DS				IFA			PSO		
	Chiller	PLR	kW	Total (kW)	PLR	kW	Total (kW)	PLR	kW	Total (kW)
5334 (70%)	1	0.6726	665.7896	3625.77	0.75935	750.87	3507.287	0.6418	638.3097	3642.579
	2	0.5955	583.2048		0.69112	677.0164		0.6621	647.2355	
	3	0.3	292.0994		**2.1E-05**	**-120.473**		0.3301	328.502	
	4	1	781.489		1	781.489		0.9906	774.8633	
	5	1	755.201		1	755.201		0.999	754.6915	
	6	0.6374	547.9865		0.7579	663.1834		0.5806	498.9765	

6. Conclusion

In this paper, a new developed algorithm, DS has been proposed to solve OCL problem. The effectiveness of DS was demonstrated and tested on 6-unit chillers system. From the simulations that had been presented, it can be said that DS is able to give the best results of total power consumption minimization compared to other recent algorithms. It can be concluded that DS is a strongly recommended algorithm for solving OCL problem.

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